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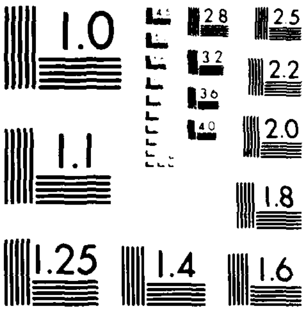

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ANTHROPOMETRY AND ITS USE IN RESPIRATOR DESIGN: A REVIEW

by

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ABSTRACT

This paper discusses the science of anthropometry and its application to the design of respirators and other headgear.

A review of relevant literature from 1940 to the present is made and a discussion of some new methods of sizing is presented.

RÉSUMÉ

La science de l'anthropométrie et son application à la conception de respirateurs et autre habillement est discutée dans ce rapport.

Une revue de la litérature pertinante datant depuis 1940 jusqu'à présent et un compte rendue de nouvelles méthodes de mesures sont aussi discutés.

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INTRODUCTION

It has often been said that the Army only recognizes three types of human: small, medium and large. This quip contains a good deal of truth and the kernel of the problem to be discussed here.

The problem is to fit the Armed Forces with clothing, respirators and all manner of protective equipment required for fighting in a modern battlefield environment, both comfortably and effectively, while at the same time keeping the number of different sizes and shapes of these items to a minimum. This may be best addressed by the judicious use of the science of anthropometry.

Anthropometry is defined simply as the measurement of the human body. Anthropometric data is generated by measuring the various limbs and muscles of the human body throughout a sample population. When a sufficiently large population is sampled, large enough to be representative of the whole, which may be the Army, the Armed Forces or the nation, the data may be treated statistically and conclusions drawn about the distribution of sizes within the population. Once this distribution of sizes is known, it is then possible to make decisions as to how it should be broken down into smaller intervals corresponding to the size of the particular item being considered.

For respirators and other head gear, we need only be concerned with head and face dimensions. But, clearly, for any one head there are different criteria for fit, and therefore design, for different pieces of equipment. Consider a rigid protective helmet and a gas mask. For any one size, a helmet must fit over a maximum critical dimension, whereas for a pliable gas mask the fit must be good over the lowest extremity. Despite these differences, the methods of assessing the data and deciding on sizes are very similar for both. Thus work relating to sizing systems of helmets and masks will be reviewed and discussed.

BACKGROUND AND HISTORY

One of the earlier anthropometric surveys of faces and heads was carried out in 1945 by the Chemical Warfare Service of the US Army in conjunction with the Massachusetts Institute of Technology(1). In this survey, researchers studied 40 different head and face variables on 3075 enlisted men. Measurements were taken with calipers and a Cartesian faceometer and the information coded and stored on IBM punched cards to facilitate mechanical sorting. By using the IBM card counting sorter, particular dimensions in any measurement could be selected. The data were then displayed on cumulative percentage graphs. The data also served as the basis for the construction of ten headforms.

For one headform, the averages for the measurements of the entire group were used and for the other nine, which represent divergent types, average measurements of selected subgroups were used. In selecting the subgroups, three variables- bizygomatic, tragion- nasal root and nasion-menton, were used for subgroup definition. These define the basic breadth, depth and length of the face. (See Appendix for illustrations of these variables.) The range of each variable had been separated into twelve groups ranging from small to large, groups 1- 4 being considered small and 9- 12 large. The small headform was made up from the average measurements of those individuals in the series who were classified small in the above mentioned dimensions: the large was made up in a similar fashion.

Another five headforms were made up from various combinations of the basic dimensions. The three basic dimensions and the three sizes gave a theoretical group of twenty- seven combinations based on three size classifications (small, medium and large). The last five headforms were the result of a compromise between their diversity and occurrence as the most extreme types are also the rarest.

Clay models were made up under the supervision of the anthropologist who made most of the actual measurements so that the surface contours could be adjusted where measurements were made with pressure.

This survey formed the basis for head sizing requirements for the US Army during most of the 1950's.

A more sophisticated approach was made to a similar problem, namely the sizing of rigid helmets, for the US Air Force by Zeigin and Alexander in 1960(2). They developed a system for sizing and design of rigid and semi- rigid helmets based on a single key dimension, in this case head circumference, and a statistical- anthropometric approach to sizing.

In earlier times, a rigorous sizing program was not used as the soft leather helmets used by fliers then presented much less of a problem as regards fit than a rigid oxygen mask or protective helmet. But in 1942, a seven- size program was set up and headforms sculpted on the basis of 50 dimensions from data obtained in a facial survey of 1454 Army Air Force Aviation cadets plus 417 additional subjects(3). A three size series of oxygen masks (oral-nasal masks) was developed from three facelengths and from various combinations of facelength and the 49 other dimensions, the seven headforms were constructed.

Facelength is generally accepted to be the key dimension for the fitting of oxygen masks whereas head circumference is of equivalent importance in sizing helmets. However, these dimensions are not well correlated and there are statistical reasons why the same headforms with faces are not applicable to helmet problems.

In 1944, the Army Air Force attempted to introduce an objective sizing system for its flying personnel(4). Using the 1942 survey, a four- size program was devised and four headforms sculpted to the mean values of 18 dimensions. This system was used for sizing the M- 1 Army helmets.

Despite the success in sizing helmets, it was still found that problems remained when trying to fit hard- shell crash helmets. There was a need to protect the pilot from 'buffeting' and other injury and to supply oxygen and pressurization. For this the 1944 series proved inadequate for two main reasons:

(1) it was based on measurements on an Air Force population known to be significantly different from the population measured in 1950 and

(2) the problem of rigid, non- close fitting shells requires joint consideration of the head and face.

The requirements for a close- fitting liner in such a system comes from the physiological need to limit dead air space and provide comfortable support. The 1950 survey data were re- analysed in these terms and the end result was the 1954 head- length, head- breadth shell- liner program.

This anaylsis dictated 18 liner sizes on the basis of six head lengths and three cephalic index groups (cephalic index being the ratio of head length to head breadth). The head length dimension was divided up into 1/4- inch increments and the head breadth dimension into narrow, intermediate and round types. Two extreme values were discarded leaving 16 sizes of liner. Only six shell sizes were used: small, medium and large with a short and long face. Each shell was designed to cover six liners in order to minimize the bulk of any one helmet.

Now, when the sizes for the liner were chosen a certain rationale was used. For all dimensions except head height, the mean value plus one standard deviation was used and for head height, the mean plus two standard deviations was used, except when a dimension involved a horizontal dimension as well as head height, in which case the mean plus 1.5 standard deviations was used. For the shell dimensions, the upper values of head length and head breadth were used and, for all other dimensions except those associated with a face length, the mean plus two standard deviations was chosen. For face length, the mean plus two standard deviations was used for long- faced shells and an appropriately smaller ratio for the short- faced ones. In all, 41 dimensions for sculpting the liner and shell headform series were used.

Because of poor correlation among head and face dimensions, certain of these were sculpturally incompatible, and so the project engineer had to decide which dimensions would be adhered to and which would be compromised. And because of a short time scale for this project, it was impossible to modify headforms as is done during a standard development program. In addition, certain modifications were made in the final helmet design which adversely affected sizing.

In the statistical assessment and the selection of size subgroups, three basic statistical problems were addressed:

1- The need to cope with a large number of body dimensions;

2- A small number of sizes are required to fit all potential users;

3- The sizing system has to be consistent with convenient field fitting.

The start of any statistical sizing procedure rests on the selection of one or more key dimensions. Individual sizes are then specified within a range of key dimensions, ie sizing programs are constructed. The three important considerations were:

1- The smaller the intervals, the easier the design;

2- The smaller the number of sizes, the smaller the manufacturing costs;

3- The larger the number of people in the particular size range, the fewer that need custom fitting.

Of course, these are in mutual conflict and trade- offs have to be made to arrive at a viable compromise.

Head circumference was chosen as the key dimension. The distribution was truncated at both ends, reducing the range by 25% but with the loss of only 3% of the sample. Six one-half- inch intervals were chosen and later reduced to three one- inch intervals.

If there are three major sizes (small, medium and large), each size subsample constitutes a 'population'. The authors worked out the small, average and large values for a given size subsample, the high and low values being computed from the mean, m, ±ns, where s was the standard deviation within the size range. Defining the small and large in terms of the first and 99th percentiles (m ±2.33s) instead of the fifth to 95th percentiles, increases the proportion of people whose head lengths (for example) fall between the small and large values from 90% to 98%, but the range will increase 40%.

Once the low, average and high values were determined for each dimension for each size subgroup, the problem then consists of establishing design values by making optimum choices. The variations in the design range and the pattern of increase from size to size is related to the statistical properties of the data as:

- inherent variability of the data as expressed by s, the standard deviation; and

- the degree of relationship between a design dimension and a key dimension as expressed by r, the correlation coefficient.

In fact, r is rather low as regards head and face dimensions. The difference between successive size values is directly proportional to both of these: the higher the correlation of head circumference and another dimension and the larger the standard deviation, the larger the interval between sizes. The width of the design range is proportional to the standard deviation but becomes smaller the higher the value of the correlation coefficient.

In the selection of key dimensions, variation in a frequently large number of dimensions within the people who make up a single size group is important. Control of the variation is the most important single factor in choosing key dimensions and in setting up sizing intervals.

Control of variability for one size range may be direct or indirect. For example, control over head circumference may be achieved by control of head length and head breadth. The most useful statistical method of control is by means of the standard error of the estimate, SE, where

$$SE = s(1 - r^2)^{1/2}$$

and the standard error of estimate is the standard deviation of, eg head breadth of men who have a particular value of head length. The standard error of estimate is closely related to the standard deviation within a particular interval and can provide guidance when selecting key dimensions. In fact it may be said that:

1- For a given set of key dimensions, the standard deviation within a particular interval is always greater than the standard error of estimate and

2- When a single key dimension is selected, the standard error of estimate is almost the same as the standard deviation for a particular range.

So a table of standard errors of estimate, based on all likely choices of key dimensions, for all design dimensions, provides a fairly clear picture of the indirect control of the variability of the various dimensions that can be achieved. This shows:

1- the choice of key dimensions which gives the least variation of standard deviation within a particular range;

2- whether it is possible to reduce the variability by another choice of key dimension;

3- the cost, in terms of variability, of choosing another key dimension.

But whatever key dimension is chosen, the authors are quick to point out the statistically optimum choice can call for key dimensions that are awkward to measure in the field, which are not satisfactory as a basis for tariffs (the number of subjects in the sizing category: the total sample size) or have other defects. From these considerations, the authors deduced that 3.30 times the minimum standard error of estimate represents the smallest effective design range.

In considering sizing for helmets, two logical combinations were, from the point of view of measurement ease, head length and head breadth and head circumference alone. It was found that a six- size program based on head circumference alone gives a standard deviation within a range almost as small as the standard error of estimate.

Should there be one or two key dimensions? A major deterrent for any more than one is the huge number of sizes that are generated. Small, medium and large sizes for three key dimensions give twenty- seven sizes and for four key dimensions give sixty- four sizes.

It is clear that head sizing is a complex problem. The advantages of using only one key dimension, namely head circumference, for head sizing were listed as:

- The probability of mistakes in measurement is less with only one dimension;

- Only an ordinary measuring tape is required. Also, in the field, people frequently do not use fitting instructions but use the simplest of procedures that will solve the problem;

- Head length and head breadth appear to be really critical only in entirely rigid helmets having no adjustability in their support;

- The number of sizes required. With head length and breadth it is possible to have four- and six- size programs but not to eliminate sizes without causing excessive bulk in the remaining helmets.

In the selection of the sizing program it had to be remembered that the adjustability of the helmet was also a function of the liner. Three sizing programs were developed:

- a six- size program based on mean values;

- a three- size program based on mean values;

- a six- size liner program.

The 1950 survey suggested that the six- size system was a good compromise, but finally a three- size program was decided upon.

Each interval was then treated as a separate sample and means and standard deviations were determined for all dimensions. The mean plus or minus two standard deviations was taken as the range as before. But to reduce bulk in the helmets, the range was chosen to be the mean plus or minus 1.65 standard deviations (5th to the 95th percentile) from which it was found that 95% of the population was still fitted. Thus in the use of the data for the sizing program the headform values are not the mid- points of the ranges to be accommodated: so unequal adjustability of the helmet liners was required.

Basically, for most dimensions, the mean plus one standard deviation was used but some compromises were deemed necessary. The top of each size range for head circumference was adhered to so all dimensions which help make up the shape and size of the head with head circumference must be considered in the same terms as head circumference or else incompatibilities occur. The regression equation values of these dimensions were chosen to ensure design values with adequate percentage coverage. These values were determined by using the upper limit of head circumference for each size interval. These regression equation values then represent the mean values of the various dimensions corresponding to the design values of the head circumference. A large clearance in the frontal region was chosen (mean plus 1.65 standard deviations) for three dimensions in this area to avoid discomfort. A few special considerations were made: maximum values were chosen for the ear dimensions for obvious reasons.

At this point, the headform series was ready to be sculpted. The headform series was made up as a concrete expression of the sizing program: two series, a six- and a three- size, were constructed. Plaster of Paris was used as the basic material and most of the dimensions could satisfy the requirement of being within 0.1 inch of the theoretical value. Subsequently, validation tests were performed on the prototype. The entire developmental program was put to a final test during the validation phase to determine fit and how the item protects the wearer. This process was divided into four steps:

1- Selection of a representative sample;

2- Measurement of key dimensions and critical ones;

3- Determination of the indicated size;

4- Fit and comfort evaluation.

The selection of the sample was important. Key dimensions were measured with selected critical dimensions which included coverage of the extremes of the intervals of the key dimension. A fitting chart, which presents the key dimensions divided into size intervals, is used in formulating the sizing program. When key dimensions overlap, a choice has to be made as to which size is considered the indicated one, and this has to be adhered to throughout the program.

Further to this work, M Alexander et al(5) investigated some of the problems associated with the production of specially sized items. It had been found that contractors and manufacturers adapt data to their own sizing standards without fully appreciating the implications of the statistics. Here, an attempt was made to standardize the sizing of all personal, protective equipment, such as gas masks, helmets and clothing. For such purposes, mannikins were found to be useful only in reflecting gross clearance problems rather than designing close- fitting personal equipment.

Up till 1961, all measurements, except those taken by the Chemical Warfare Service, were taken by hand. The CWS measurements were taken by a Cartesian Faceometer which located facial landmarks in space. The criticism was made that earlier approaches to the sizing problem were inadequate: that there are limits to the extent to which the statistics may be manipulated and at the same time be integrated into non- distorted three- dimensional forms.

Sizing systems and programs were defined: the former being the selection of key dimensions which serve as the basis for statistical analysis, and the latter being the division of ranges of key dimensions into appropriate intervals, after which the desired values of the remaining important dimensions within each size are obtained. Then, each size is treated as a separate subsample and the mean and standard deviation computed within each size. After this, then, the headform series may be sculpted.

The data used for this was the 1954 USAF survey of 4000 Air Force flying personnel and part of a 1957 photometric survey of 2000 Air Force flying personnel.

These data were used to assist in the design of an oral-nasal oxygen mask. Two main problems were presented to the designers: comfort and fit.

For comfort, the mask had to rest on the bony bridge of the nose, and for a good, leakproof fit, the mask had to cover the mouth in a relaxed and a smiling position. In order to achieve the first goal for most of the population, X- ray photographs of 23 adult males were analysed and these showed a vertical distance between nasal root depression and the end of the nasal bone to be 0.76 ±0.11 inch. It was found that only 2% of the population had values less than the mean minus two standard deviations. Thus it was possible to design the mask in one- half- inch intervals of face length (menton- nasal root depression) and design the mask to the lower limit of this dimension.

For fit, the increase in lip length for a sample of 27 men was found to be 0.41 ±0.20 inch during smiling. The mean plus two standard deviations was chosen for lip length and provided a satisfactory fit. So a sizing system with the key dimensions of face length and lip length was established wherein six sizes were generated to include 96% of the population. The actual design dimensions for face length and lip length were the lower limit for the former and the upper limit for the latter. For other critical dimensions, the mean minus two standard deviations was chosen for nasal root breadth and also for interocular breadth so as not to restrict the visibility of people small in this dimension. The mean plus two standard deviations was picked for width and protrusion of the nose as these had to accommodate maximum dimensions.

Composite dimensions such as face length were somewhat problematical. The use of the lower limit of face length presented such a problem and proportional values were computed for its component dimensions of nose length, philtrum length, lip- to- lip distance and menton- subnasale distance. Each of these dimensions was expressed as a ratio of the mean face length for the particular size with the final design value being determined by multiplying this ratio with the design value of face length for that particular size. Here, of course, face length is equal to nose length plus menton- subnasale length. For all other dimensions, the mean minus one standard deviation was chosen.

Again, attention was drawn to the particularly complex problems of sizing for hard- shell helmets and one key dimension, head circumference, was chosen. The advantages of one key dimension have already been discussed. The analysis and conclusions of Zeigen et al(2) were re-analysed and discussed.

It was observed that considerable confusion existed among designers when handling anthropometric data for specialized, close- fitting personal equipment. The primary approach to this problem has been to translate the tables of statistical data into three- dimensional forms. Here, statistical sizing programs were set up on the basis of key dimensions which serve as fitting dimensions in the field; sizing programs indicating the minimum and maximum size values were established by dividing key dimensions into appropriate size intervals and a series of forms sculpted to a particular sizing program. For the faceforms for the oral-nasal oxygen mask, face length and lip length were the key dimensions and for the headforms for helmet sizing, head circumference was the key dimension.

Similar conclusions were reached by Coffey and Nash in Canada(6). An anthropometric survey was made of approximately one thousand Canadian soldiers using two newly designed instruments for obtaining data of facial contours. The data collected included:

* the contour of the brow on a transverse section 3.58 centimeters above the nasion;

* the contour of the jaw on the menton/gonion line;

* the location of the nasion, menton and gonion relative to the external meatus of the ear;

* the location of two points on the forehead (low and top), one on the nasal bridge and one on the eye orbit (zygomatic), all relative to the nasion point.

To obtain these data, the following measurements were made:

* the position of the gonion relative to the external meatus of the ear;

* the distances from the axis of the ear meati to parallel axes at the menton and nasion;

* the angle between the meatus/menton and meatus/nasion lines;

* the angles from the the nasion to the brow at 6.24 and 3.58cm respectively from the nasion;

* the angle from the nasion axis at an arbitrary distance to the eye orbit;

* the angle from the nasion at an arbitrary distance to the nasal bridge.

These data were entered on punched cards and sorted according to nasion/menton (ie face length) sizes.

An important question addressed immediately was how would the mold and mask differ from measured facial dimensions? or, in other words, what must be the design dimensions for a particular mask size?

Three procedures were then carried out:

* an analysis of the adequacy of the sample with respect to its face length distribution in terms of a larger population sample;

* an analysis of the adequacy of the sample with respect to racial origin (French- Canadian or non- French-Canadian);

* and an analysis of the sample for corps distribution.

An inspection and a non- parametric sign test of differences between face length intervals in the predicted and actual populations suggested that no corrections were required for the difference in racial origin. A comparison by arms and services between the sample population and the army at large revealed slightly leaner faces in arms than in services, probably due to the greater percentage of young men and the higher incidence of physical fitness in the arms. The sizing meter that had been developed for the purposes of this survey was graduated on an arbitrary scale of 0 to 15 and limits for this sample were considered to be graduations 4 to 11- the normal size limits. The sizing meter measured face length. This provided the normal sample data.

These normal sample data were taken and the following statistics for all of the measurements calculated: mean; mode; median; frequency distribution by face length intervals; percentage frequency distribution by face length intervals; and cumulative frequency distribution by face length intervals. These were calculated for all point measures and for arbitrary points at one- half- inch intervals on the brow and chin diagram lines using normal statistics.

At this point the medium face form was ready for sculpting. This face, which in theory was too large or too small for all but 15% of the population, was then used as the basis for sizing decisions. Certain dimensions were not directly transferable to a mask by reason of both the statistical distributions of size and particular physical characteristics of the mask. For example, a mask will stretch to fit somewhat larger sizes, but not shrink to fit smaller ones. A wider degree of fit is possible horizontally than vertically.

These dimensions were the basis of the survey and the mean statistics of this triangle were accepted without modification. They were:

Ear/nasion	10.6 cm
Ear/chin	11.9 cm
Included angle	63 degrees 31 minutes
Nasion/menton	11.9 cm

The other dimensions in the survey: gonion location, low brow position, high brow position etc, were allotted the mean dimension except where the nature of the dimension demanded a maximum or minimum fit.

The point for the lower forehead position was located by determining the mean angle from the nasion/ear plane about the nasion subtended by an arm 3.58cm long. This angle was found to be 96.5 ±4.5 degrees.

The upper forehead position was similar to the lower and determined the same way except for an arm 6.18 cm long. The angle chosen was the mean minus 5.5 degrees.

When the forehead was being considered, it was important that the mask fit the most receding forehead of the group. The penalties for constructing patterns, molds and masks too upright are bulges, wrinkles and leaks when the mask is fitted to foreheads of a lesser angle. Thus a 5.5 degree reduction from the mean provided a contact fit for 90% of the population. These modifications were incorporated into a new head form which was used as the basis of a modified medium mask.

FITTING TRIALS

After a small trial in the Arctic under winter conditions, some more modifications were made to the nosecup to prevent leakage and a larger scale fitting trial was conducted on 841 subjects. The trial was carried out to evaluate the mask fit; the location of the eye position with reference to the lenses; nosecup fit; misting, wetting and frosting; and a gas chamber test.

It was found that 87% of the subjects achieved a satisfactory fit with the medium mask, the others possibly or definitely needing the small or large mask. A satisfactory fit was achieved with the nosecup after donning instructions and practice.

The fit of the nosecup is essential for frost- free operation and this fit was tested by inhaling cigaret smoke and exhaling through the nosecup. 11% of the subjects showed leakage after two fittings, but this percentage dropped rapidly after only minimal training: and in the gas chamber test, over 98% of the total population achieved a gas-tight fit after two fittings.

When a successful fit had been achieved, each subject was required to have the head harness pressure measured. This was performed with a pneumatic pad and mercury manometer. The average pressure in the normal population was found to be 1.19 inches of mercury.

This experimental mask generally provided a good fit for the population but some problems were encountered, mainly with the nosecup.

A different, but very important, type of problem was addressed by McConville(7) viz, will the personal protective equipment designed to fit personnel of one member nation (of Air Standardization Co- ordinating Committee) fit the personnel of all member nations as well?

Data from eleven different anthropometric surveys dating from 1950 to 1974 and originating in the USA, Canada, the UK, Australia and New Zealand were used. It was found that these data varied widely from survey to survey in the number of head and face variables measured and the completeness of measuring techniques and descriptions. These surveys included 1950, 1965, 1967 USAF; 1964 USN; 1973 RNZAF; 1971

RAAF(2); 1971,1972 RAF; 1962 RCAF; and 1974 CF. This difficulty exacerbates the problems of comparing survey to survey. Here, measurements were considered comparable on the basis of common variable names. Anthropometric comparisons are usually beset by two main problems: (a) variability in measuring techniques and (b), variability in the composition of different populations. Sometimes the same variable name in different surveys refers to measurements that have been taken by differing techniques, for instance, the value obtained for the minimum frontal arc for the 1965 USAF survey was 12% less than that for the 1967 USAF survey, strongly suggesting that different landmarks were used. The differences in the bitragion- minimum frontal were only 1%.

Furthermore, head circumference for the 1971 RAF survey and the 1972 RAF head survey were nearly identical, whereas head length and head breadth means of the 1972 RAF head survey are approximately one standard deviation larger than comparable dimensions of the 1971 RAF study. In the RAF head study, head circumferences were measured in the traditional manner while the other two variables were measured from photographs.

The second area of variability, in the composition of the population, can be from the age and general body size of subject populations. This could be the result of a range of age, weight and stature between basic trainees, enlisted men and officers. But it was apparent that differences in head dimensions between ASCC groups were relatively small when viewed against the range of variability within any single sample.

The problem of head sizing proposed by Zeigen(1), (2) was widely used and a similar six- size head circumference sizing program was published by Simpson in 'Specimen Size Rolls for Aircrew Headgear Based on Analysis of the Head Measurements of 2000 RAF Aircrew.' In order to compare the two surveys, the 1967 USAF data were re- analysed to correspond to the six- sizing categories in the RAF program.

The quantity calculated was D, the 1967 USAF size category mean minus the RAF size category mean, the average difference for the six size categories, ie the average of the D values, and the average difference as a percentage of the RAF mean value. This excluded the 1972 RAF head measurements taken from photographs. The difference in tariffs (the number of subjects in the sizing category: the total sample size) ranged in absolute difference from 0.11 to 3.65 (size 6 to size 2 respectively) with an absolute average deviation of 1.56%. This analysis included 100% of the RAF sample and 99.75% of the USAF sample. The results showed that head circumference distributions of the two samples were very similar- this conclusion was further reinforced by comparison of the mean head circumferences of the six subgroups.

The average absolute difference of head circumferences of the six sizes was found to be 0.04cm- a very low order of difference. The standard deviations in each of the six sizing category subgroups was virtually identical.

By control of a key or sizing dimension, such as head circumference, it is possible to effectively control its variance and that of the dimensions most highly correlated with it, but, because of the low correlation with most other head dimensions, little control is exerted over those other head dimensions.

Thus it was observed that helmet design dimensions based on category means and standard deviations would be essentially the same for the two populations. It was concluded that helmets or other headgear which are successfully fitted for an ASCC member nation's flying personnel could be fitted with equal success to the flying personnel of other ASCC nations.

A NEW APPROACH: THE XM-29 PROGRAM

A re- examination of the sizing parameters of respirators was undertaken in 1976 in the USA by Mangelsdorf, Goldberg and Santschi of Synsis Inc(8) as part of the development program of the XM-29, the experimental mask intended to replace the M17 as the US Army standard issue infantry respirator.

This work presented a new approach to the assessment of anthropometric data and its use in determining design forms by virtue of the fact that in earlier years computers were not available to carry out the enormous number of calculations required to perform multivariate analyses and generate cross correlation coefficients. These calculations were performed and led to some rather different conclusions concerning headforms and mask design.

Data were examined from 12 studies dating from 1946 to the present and compared to 25 standard headforms.

Bivariate analyses of the anthropometric data acquired were performed and comparison with headforms made. It was found that neither of the conventional techniques for determining size accommodation (univariate means and standard deviations; bivariate range ellipses) could be used to design masks to accommodate the US military population.

An analysis of facial characteristics was performed to establish both a list of facial dimensions relevant to mask design and a list of mask dimensions derived from the facial dimensions. That, coupled with a review of published anthropometric data, indicated that most have limited applicability in that they excluded many facial dimensions found to be important- particularly with regard to females.

With regard to the inclusion of female statistics it was concluded that combining male to female data in the ratio 95% to 5% (to reflect the current military composition) severely limits the ability of the new protective mask to accommodate the female population. The approach recommended would use the small extremes of the female population to establish the size for the small mask and the large extremes of the male data to establish the size for the large mask.

A comparison of the ranges and means for the black and non- black population subgroups (both male and female) indicated that facepiece sizing need not differentiate between these two groups. However, as far as nosecup design and the location of major mask components in the oral- nasal area was concerned, the design should accommodate the maximum of the black subgroup size. These conclusions were derived from surveys covering 62631 subjects of whom 18% were women. In conjunction with these studies, a study of the headform series developed by the Forsyth Dental Clinic to represent children and adult males and females was made. This was because the CWS- MIT headforms were based entirely on male anthropometry and were not representative of females.

The data analysis was performed in three stages:

-1 selection of facial dimensions important for respirators;

-2 comparison of facial dimensions for headforms and human subjects and;

-3 identification of 'best' headforms on which to base respirator design.

Twenty different head dimensions were used.

Difficulties were encountered when the CWS- MIT and Forsyth Dental Clinic headforms were assessed to select large and small headforms. It was found that there was inadequate representation by the headforms of the population upon which they were based and that the then current techniques used in deriving sizing criteria for devices such as respirators were inadequate. Both sets of headforms were based on too few variables to select sizes.

For the MIT headforms, a major mistake was made in selecting the means of ranges instead of the mid- points of the dimensional ranges within each subgroup. Since any partition (which does not include the mean) of an approximately normal disribution will contain more data points close to the mean of the total distribution than farther away, an average of data values over such a partition will approach the values along the partition boundary closest to the mean. The result of choosing the means was that the small facepiece, designed around the small headform, had to fit individuals with facial dimensions substantially smaller than the headform but only slightly larger. Thus the distribution of headforms by size was substantially smaller than the distribution of face sizes within the male military population because their specified dimensions are all too close to the mean values for the sample as a whole. The US 'minimum/maximum' sizing technique requires the 2nd to the 98th percentile to be fitted. Because of the relatively low level of correlation between most head dimensions most people who would qualify for a 'large' mask are, in fact, large in only one or two major head dimensions, most of their other dimensions being 'medium'.

If one requires more variables to describe an object, the range of variables for each dimension increases in order that the percentage of total objects in the description remain constant. For example, consider the dimension face length. For face length alone, 90% of all faces fall bewteen the 5th and 95th percentiles. If face width is included as well, then the ranges of face length and face width necessary to describe 90% of the population move out to the 1.6th and 98.4th percentiles. Conversely, if the 2nd to 98th percentile ranges of each of six dimensions are used in the description, then less than 50% of the population will actually be represented. Thus it was concluded that the CWS- MIT and Forsyth headform series were both inappropriate for use in the design of small and large respirators.

NEW DESIGN SPECIFICATIONS

These preliminary specifications included mid- point values of dimensional ranges for design dimensions of respirators and headforms. The sizing system for respirators used face length as the key dimension and this was divided into three approximately equal ranges from the 2nd percentile female to the 98th percentile male. The remaining dimensions which were specified, ranged from the 2nd percentile female for the small size to the 98th percentile male for the large size. The percentiles were taken directly from the data sheets of the McClellan survey for females and were calculated from male means and standard deviations. Derived dimensions were derived from means, standard deviations and correlation coefficients rather than by taking the sums of the dimensions for each subject in the female survey. The 2nd and 98th percentile values were also calculated as means minus and plus 2.05 standard deviations. Design points were taken as the mid-points of the dimensional ranges.

A new procedure for sizing respirators was recommended and consisted of six stages. Firstly, the means, standard deviations, minima and maxima for the required variables were found. The male and female subgroups were represented separately. Secondly, measurements that needed to be computed were computed for each subgroup. Thirdly, one or more key variables were chosen. In selecting the number of key dimensions it was noted that the total number of sizes would be the product of the number of sizes for each of the key dimensions (eg 3 face lengths and 2 lip lengths giving 6 sizes). A corollary to this was that the accommodation ranges of all non- key variables typically spans almost the entire range for the user population. Fourthly, once the key variables were selcted, plots were made of the two-dimensional projections of the multivariate distribution. For one key variable, each plot showed an ellipse for each population subgroup where the independent variable was the key variable and the dependent variable was one of the remaining variables. Fifthly, the plots of each variable against the key variable were used to establish the accommodation range for each variable in turn for each size. The total range of the independent variable was divided into n equal segments where n was the number of sizes for the independent variable. Lines drawn perpendicular to the axis of the independent variable at the end points of the n segments intersect the ellipses at points defining the minimum and maximum values of those variables to be accommodated by a certain size. Design values were min-points. Sixthly, having derived the design point for each size, it was deemed desirable to construct extremes against which to test the respirator. In terms of the bivariate analyses, the extreme combinations lie on the surface of an n- dimensional poly- ellipsoid defined by the intersection and overlapping of the ellipsoids for each of the subpopulations.

Even with the new analysis, the three sizes for the military population were retained. The effect of the inclusion of females has been to widen the total range of facial dimensions. The large and small headforms for this approach correspond to harmonic combinations of the mean values for females and the mean values for males. The dimensions of the 'medium' size then corresponded to the mid- points between the upper extremes for males and the lower extremes for females. The accommodation range for all dimensions except face length would range from the lower to upper extreme values of female dimensions for the small mask and of male dimensions for the large mask. Face length ranges were 81 to 109mm for the small, 105 to 125mm for the medium and 120 to 143mm for the large.

As the small, medium and large masks are not proportionally scaled versions of each other, the speech transmitter and canister mourt are not located similarly relative to facial landmarks on the different sizes.

In order to select a headform from those available to represent each of the small, medium and large models for the new mask design, univariate and bivariate comparisons were made between the headform dimensions and the anthropometric data. Bivariate ellipses were derived to encompass 95% of the population.

Two populations were considered. One was 95% male and 5% female, reflecting the current military distribution, and one was 50% male and 50% female. It was found that the headforms were poorly distributed over the ranges.

In addition to this poor distribution, it was found that there was considerable variation between specifications and actual headform dimensions. Despite these shortcomings, an analysis of the candidate headforms was performed.

The measurements selected were:

1 Menton- nasal root length (face length);

2 Bitragion- submandibular arc;

3 Bitragion- menton arc;

4 Bitragion- subnasale arc;

5 Bitragion- minimum frontal arc.

Except for face length, none of these dimensions were determined and applied to the design of candidate headforms.

Several sets of bivariate relationships for these variables were developed: only two were considered useful. One set had face length as the independent variable and the other, bitragion- submandibular arc. In each case the independent variable was sectioned into three equal segments comprising the population range to represent each of the three sizes.

The bivariate ellipses were graphically presented and positions of the various headforms (CWS series) were plotted on these graphs. A suitability index, R, represented an occurrence of a headform within a 0.5 or 1.0cm radius of the optimum selection point. In many instances, the 'best' headform did not occur within the 0.5 or 1.0cm radius. Then the best headform would be a poor choice on which to base a design of protective masks. From the bivariate and univariate analyses, a set of design dimensions for small, medium and large masks was presented. These dimensions were based on the best estimates from the bivariate analyses.

The small-size mask design dimensions in the above-mentioned survey were determined using basically female statistics. An anthropometric survey of Canadian Forces women(9) also demonstrated significant differences between males and females. The survey recorded 42 body dimensions of 137 women. The results were displayed as percentile tables.

It was found that the 50th percentile female appeared to correspond with the 5th percentile male in many body dimensions. A statistical comparison of the male and female distributions showed the female population to be significantly different in all body dimensions.

Further work on sizing and fit testing was performed by Alexander and McConville(10) on an oral- nasal oxygen mask for the US Air Force. Here, fit and performance were critical. A new mask was developed to operate in the higher G- force environment encountered in the new generation of fighter aircraft. The new mask was the MBU- 12/P oral-nasal oxygen mask, a single unit facepiece in which a deformable silicone elastomer face form is bonded to a rigid polysulfone hard shell. Four sizes were manufactured. Sizing data was taken from the 1967 USAF Flying Personnel survey covering some 2420 subjects.

The approach to sizing this item was broken down into six steps:

1- Selection of an appropriate body of anthropometric data for analysis;

2- Selection of one or more key, or basic, sizing dimensions;

3- Selection of the range of key dimensions for the purpose of establishing a sizing category that will adequately accommodate all those individuals who fall within it;

4- Development for each sizing category of all other dimensional data for use in sizing the item;

5- Conversion of the summary data to the proper design value for the end item in terms of form or function;

6- Establishment of the sizing tariff.

In agreement with most other workers in this field, face length was chosen as the key dimension. Again, it was found that, especially for an oral- nasal mask, this was the most relevant dimension: most other head dimensions show very little correlation one to another. Four face length categories, each with a 9mm range, covered over 99% of the population. Then, individuals in each sizing category were treated as a subgroup and the mean for each of the 35 facial dimensions was computed for each subgroup of size category. The standard deviations from the four categories for each measurement were averaged to reduce the effects of the variation in category sample size and the averaged standard deviations were used with the category means to establish the design ranges for each sizing category.

The design values were developed as a particular combination of the mean value with the averaged standard deviation. The face length, which was the key dimension, was established at the mid- point of the category range and regression equations based on appropriate face length were used to establish proportions of upper and lower face length. The projections of the nose, nose breadth, lip length, and lip protrusion were established as the regression mean value plus 1.65 standard deviations or two standard deviations (95th or 97.7th percentiles) as these must be cleared by the body or the internal sealing edge of the facepiece. The breadth of the facepiece was determined by using design values for the bizygomatic breadth and a bigonial breadth equal to the mean minus one standard deviation.

Fit- testing and evaluation was performed on 66 subjects using an A- 14A oxygen regulator and flow meter. One liter per minute was allowed as a permissible flow rate. The frequencies in the fit test were slightly at variance with those found as a result of data analysis. Despite that, most subjects reported a good fit.

DISCUSSION

Serious attempts at producing codified information on human head and face sizes was undertaken in 1945 by the Chemical Warfare Service of the US Army. Between then and now many more surveys have been completed by various armies, navies and air forces each with special reference to particular subgroups, such as flying personnel, men, women, race etc.

Analysis techniques have been changed by the application of computers to the problems of data analysis, enabling researchers to carry out computations on large numbers of variables. Prior to this, analysis of single variables was the only feasible route. Correlation coefficients between the many variables of head and body dimensions were difficult and time- consuming to calculate.

The next step in the process was to take the data and its derivatives and use it to construct three- dimensional head and face forms on which mask shapes could be designed and built. These headforms were carefully sculpted to reflect the data as accurately as possible.

But the report of Synsis Inc. [illegible] [illegible], [illegible] [illegible] the US, to establish quantitative parameters for the design of a new protective mask, has revealed some flaws in the method of assessing data. A check of the actual sizes of some of the Forsyth series and Chemical Warfare series headforms revealed that many of the design dimensions did not correspond at all closely with the numerical data. Further, the use of means for fixing all of the design dimensions produced headforms that were not reflective of the real population. For example, someone small in the key dimension of face length is not necessarily small in the other head dimensions. In fact, this is relatively unlikely as head dimensions have little correlation one to another.

This study, and that of McConville, Churchill and Taylor(7), revealed that women have a very significant effect on anthropometric data. In general, for most body dimensions, the 50th percentile female appears to correspond with the 5th percentile male. For mask design, this fact alone greatly influences the design of the small mask which must, essentially, be suitable for a large percentage of the female population. The sizing programme recommended by the Synsis report divides the face length into three approximately equal ranges extending from the [illegible] percentile female value to the [illegible] percentile male value. This approach preserves the simplicity of only three sizes of mask and can accommodate any population of arbitrary mix of female and male. The percentage distribution of males and females in any particular population can be used to generate the sizing tariffs, which dictate what percentage of small, medium and large masks should be procured. Thus the situation of melding female and male anthropometric data into one population is avoided.

Considerations for fitting females are important as the female population, even though at a fairly small value of 5%, is increasing.

The design of devices such as protective masks that involve the use of such large numbers of independent variables always demands compromise. The more accurate and detailed the information available to the designer, the easier is the task of making good decisions.

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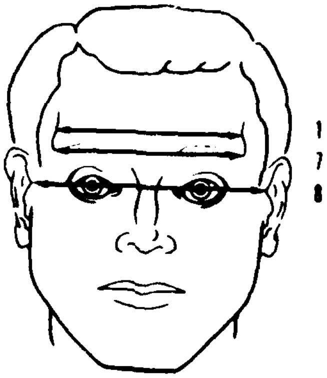
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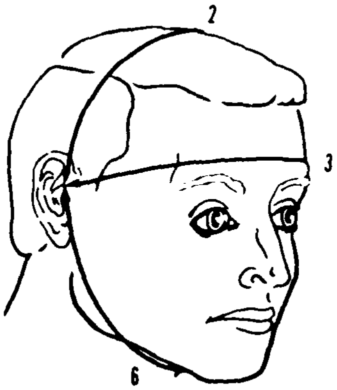
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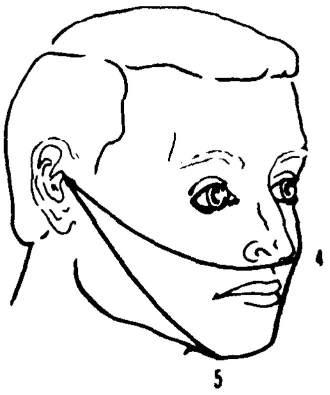
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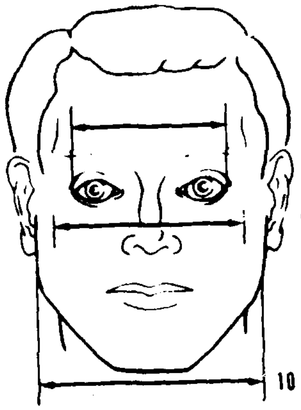
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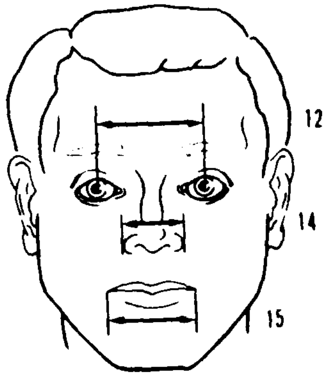
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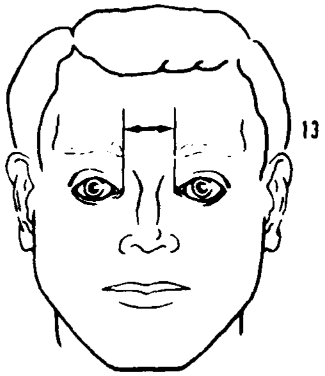
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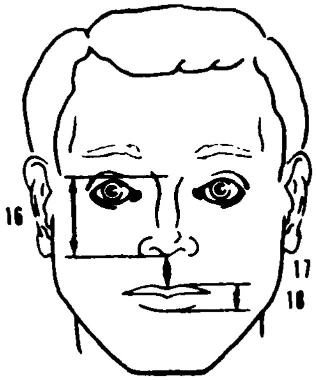
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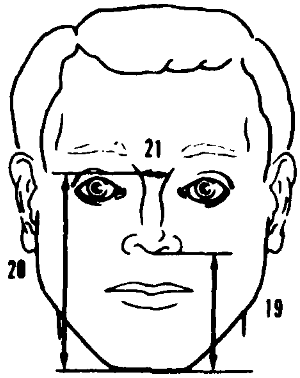
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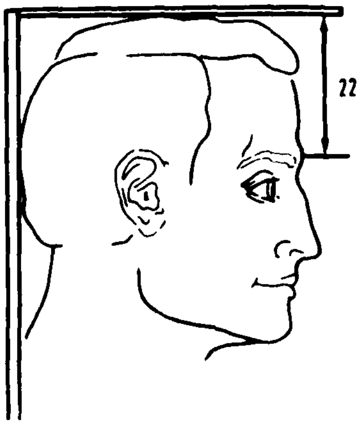
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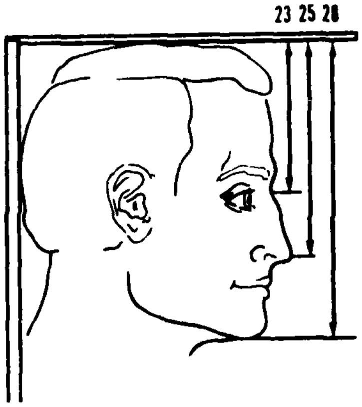
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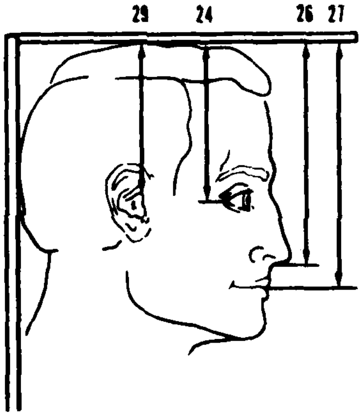
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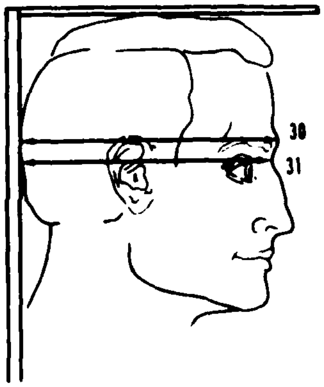
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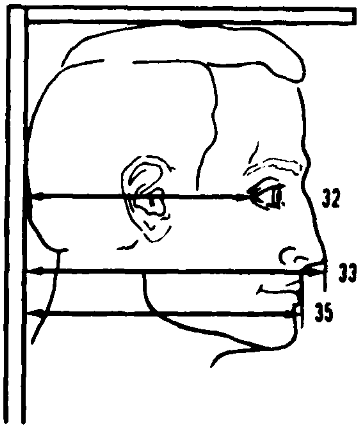
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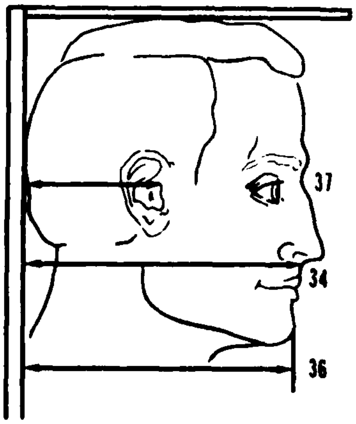
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DESCRIPTION OF ANTHROPOMETRIC PARAMETERS:

1. MINIMUM FRONTAL CURVATURE: the distance across the forehead between the points of greatest indentation of the temporal crests just above the eyebrows.

2. BITRAGION-CORONAL CURVATURE: the distance across the top of the head from right tragion (the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion of the left ear.

3. BITRAGION-MINIMUM FRONTAL CURVATURE: the distance across the forehead measured just superior to the brow ridges, from right tragion(the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion of the left ear.

4. BITRAGION-SUBNASALE CURVATURE: the distance across the face just below the nose from right tragion (the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion on the left ear.

5. BITRAGION- MENTON CURVATURE: the distance from right tragion(the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion on the left ear as measured across the tip of the chin.

6. BITRAGION-SUBMANDIBULAR CURVATURE: the distance from right tragion (the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion on the left ear as measured along the juncture of the jaw with the neck.

7. MAXIMUM FRONTAL BREADTH: the distance across the face between the lateral bony ends of the brow ridges.

8. BITRAGION BREADTH: the distance across the face from right tragion (the cartilaginous notch just in front of the upper edge of the right ear hole) to the corresponding tragion of the left ear.

9. BIZYGOMATIC BREADTH: the maximum horizontal breadth of the face between the most laterally projecting bones of the cheeks.

10. BIGONIAL BREADTH: the maximum horizontal width of the jaw.

11. BIOCULAR BREADTH: the distance between the outer corners of the eyes.

12. INTERPUPILLARY BREADTH: the distance between the centers of the pupils with the subject looking straight ahead.

13. INTEROCULAR BREADTH: the distance between the inner corners of the eyes.

14. NOSE BREADTH: the maximum horizontal breadth of the nose.

15. LIP LENGTH: the maximum distance between the corners of the mouth.

16. SUBNASALE-ROOT LENGTH: the distance from the base of the nose to the center of the nasal root (the greatest indentation between the eyes).

17. PHILTRUM LENGTH: the length of the vertical groove that runs from the upper lip to the base of the nose.

18. LIP-TO-LIP LENGTH: the maximum distance between the lower margin of the lower lip and the upper margin of the upper lip.

19. MENTON-SUBNASALE LENGTH: the vertical distance from the tip of the chin to the base of the nose.

20. MENTON-NASAL ROOT LENGTH: the distance between the tip of the chin and the deepest point of the nasal root depression.

21. NASAL ROOT BREADTH: the distance across the nasal bridge at its greatest indentation between the eyes.

22. GLABELLA TO TOP OF HEAD: the vertical distance between the top of the head and glabella (the most protruding point of the forehead between the eyebrows).

23. NASAL ROOT TO TOP OF HEAD: the vertical distance between the top of the head and the nasal root (the greatest indentation between the eyes).

24. ECTOCANTHUS TO TOP OF HEAD: the vertical distance between the top of the head and the outside corner of the eye.

25. PRONASALE TO TOP OF HEAD: the vertical distance between the top of the head and the tip of the nose.

26. SUBNASALE TO TOP OF HEAD: the vertical distance from the top of the head to the base of the nose.

27. STOMION TO TOP OF HEAD: the vertical distance between the top of the head and stomion (the point of contact in the center of the upper and lower lips).

28. MENTON TO TOP OF HEAD: the vertical distance between the top of the head and the tip of the chin.

29. TRAGION TO TOP OF HEAD: the vertical distance between the top of the head and tragion (the cartilaginous notch just in front of the upper edge of the ear hole).

30. GLABELLA TO WALL: the horizontal distance between the wall and glabella (the most protruding point of the forehead between the eyebrows).

31. NASAL ROOT TO WALL: the horizontal distance between the wall and nasal root (the greatest indentation between the eyes).

32. ECTOCANTHUS TO WALL: the horizontal distance between the wall and the outer corner of the eye.

33. PRONASALE TO WALL: the horizontal distance between the wall and the tip of the nose.

34. SUBNASALE TO WALL: the horizontal distance between the wall and the base of the nose.

35. LIP PROTRUSION TO WALL: the horizontal distance between the wall and the maximum protrusion of the lips.

36. CHIN PROMINENCE TO WALL: the horizontal distance between the wall and the maximum protrusion of the chin.

37. TRAGION TO WALL: the horizontal distance between the wall and tragion (the cartilaginous notch just in front of the upper edge of the ear hole).

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This paper discusses the science of anthropometry and its application to the design of respirators and other headgear. A review of relevant literature from 1940 to the present is made and a discussion of some new methods presented.

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